

CHAPTER 5. ENGINEERING ANALYSIS

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CHAPTER 5. ENGINEERING ANALYSIS

5.1 INTRODUCTION

The engineering analysis establishes the relationship between the cost and efficiency of commercial unitary air conditioners and heat pumps. This relationship serves as the basis for cost-benefit calculations in terms of individual consumers, manufacturers, and the nation.

In this chapter, the Department discusses the identification of baseline products, the methodology used to generate bills of materials (BOMs) and costs, the process for constructing industry cost-efficiency curves, and the impact of using an alternative refrigerant on the cost-efficiency relationship of certain commercial unitary air conditioners and heat pumps.

To establish the industry cost-efficiency curves, the Department used: (1) reverse engineering methodologies, (2) product information from manufacturer catalogs, and (3) computer simulations and other analytical methods to investigate the efficiency improvements resulting from one or more design options. The Department developed BOMs, which are detailed descriptions of each unit that the Department considered. After that, the Department developed a cost model that converted the BOMs into factory costs. By applying manufacturer markups to the computed factory costs, the Department constructed industry cost-efficiency curves, with statistical confidence intervals, from the factory costs. Finally, the Department used computer simulations of existing equipment with various design options to verify the predicted cost-efficiency curves.

In a subsequent life-cycle cost analysis, described in the following chapter, the Department used the industry cost-efficiency curves to determine consumer prices for commercial unitary air-conditioning equipment, by applying distribution markups and sales tax or builder markups.

In conducting the engineering analysis, the Department only considered equipment that include technologies and techniques that improve the energy-efficiency ratio (EER) of commercial unitary air-conditioning equipment. As mentioned in the screening analysis, the Department understands that there are potential energy savings associated with technologies and techniques that can improve the net annual energy performance of a system, but which generally reduce or have no effect on EER. (More information on these technologies is available in Appendix A.) However, EPCA requires the Department to consider only those which improve EER. The EPCA establishes energy-efficiency standards for commercial unitary air-conditioning equipment under 42 U.S.C. 6313(a)(1)(C) and (2)(A), and which are measured and expressed in terms of EER under 42 U.S.C. 6314(a)(4)(A). Therefore, the Department is not considering technologies that reduce or have no effect on EER at this time.

5.2 EQUIPMENT CLASSES

As discussed in the market assessment, the Department defined four equipment sub-categories for its analysis:

- single-package and split-system unitary air conditioners from $\geq 65,000$ to $< 135,000$ Btu/hr in capacity;
- single-package and split-system heat pumps from $\geq 65,000$ to $< 135,000$ Btu/hr in capacity;
- single-package and split-system unitary air conditioners from $\geq 135,000$ to $< 240,000$ Btu/hr in capacity; and
- single-package and split-system heat pumps from $\geq 135,000$ to $< 240,000$ Btu/hr in capacity.

The engineering analysis considered only single-package equipment in the estimate of the cost-efficiency relationship for the equipment sub-categories listed above. The Department focused on the single-package equipment because this represents the highest sales volume within the commercial unitary market segment, as shown in Table 5.2.1.

Table 5.2.1 Census Data for Equipment Sub-Categories

Equipment Class	$\geq 65,000$ to $< 135,000$ Btu/hr	$\geq 135,000$ to $< 240,000$ Btu/hr*	Total Unit Sales	% of Total Sales
Single-Package Unitary AC	135,563	60,544	197,107	68
Split-System Unitary AC	41,950	14,038	55,988	19
Single-Package and Split-System Heat Pumps	21,620		21,620	13
Total			288,705	100

Source: 2001 Census Data for Refrigeration, Air Conditioning, and Warm Air Heating Equipment

* Census data include units with capacities up to 249,999 Btu/hr.

Although DOE did not explicitly analyze split systems in the engineering analysis, the Department estimates that the results of the single-package analysis apply to the split systems and that the systems have equivalent cost-efficiency relationships. While the size constraints (i.e., cabinet requirements) may be different for the two types of systems, the technologies and design choices required to increase the efficiency are similar. Both systems will realize essentially equivalent benefits from such improvements as higher-efficiency compressors, larger coil surface area, and other applied technologies.

The Department does not consider the single-package and split heat pump systems to be equivalent to the single-package air-conditioning equipment analyzed in the engineering

analysis. However, the Department intends to adjust the minimum efficiency of the heat pump equipment in a manner consistent with the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE) methodology used to set the ASHRAE 90.1-1999 levels for unitary systems with heat pump heating.

Niche equipment includes vertical package units and specialized equipment dedicated to controlling temperatures and humidity levels not associated with human comfort, i.e., in laboratories, sensitive storage areas, and computer rooms. The Department did not consider these niche units in the establishment of the cost-efficiency relationship. At this point, the Department has not decided how to establish efficiency levels for these units.

5.3 IDENTIFICATION OF BASELINE UNITS

The identification of the baseline unit requires establishing both the baseline efficiency level (minimum EER rating) and the baseline capacity used to represent the different capacities of the equipment classes ($\geq 65,000$ to $< 135,000$ Btu/hr and $\geq 135,000$ to $< 240,000$ Btu/hr).

5.3.1 Efficiency Levels

The Department is required to increase the efficiency standards for the four equipment classes to at least meet the minimum efficiency level specified in the latest edition of the ASHRAE 90.1 standard. The most recent version of the standard, ASHRAE 90.1-1999, became effective as of October 29, 2001. The Department must either accept these minimum levels or demonstrate that higher levels are technologically feasible and economically justified, and would save a significant amount of energy. Because the Department is not able to consider levels lower than that of ASHRAE 90.1-1999, it set the baseline efficiency levels at the minimum levels specified in ASHRAE 90.1-1999.

The Department understands that there are certain manufacturing costs associated with any increase in the efficiency of air-conditioning equipment from current EPCA levels to the ASHRAE 90.1-1999 levels. For this reason, DOE included in the engineering analysis equipment with efficiency levels greater than or equal to the EPCA efficiency levels but lower than the baseline ASHRAE 90.1 levels, along with equipment with efficiency levels greater than or equal to the baseline ASHRAE 90.1 levels. The Department determined the manufactured costs of the lower-efficiency equipment using the same methodology as it did for the higher-efficiency equipment, and considered these costs when constructing the industry cost-efficiency curves. Since it set the baseline at the ASHRAE 90.1 levels, however, the Department used “incremental cost” (the cost of raising equipment efficiency from the ASHRAE level to some incrementally-higher efficiency level) to describe the industry cost-efficiency curves (see Figure 5.3.1). As such, the portion of the industry cost-efficiency curve below the ASHRAE Standard 90.1 efficiency level is only relevant for establishing the trend of the curve near the baseline efficiency level. Any decrease in efficiency below the baseline level is illustrated by a negative incremental cost.

At the time the engineering analysis was conducted, the highest efficiency level for commercial unitary air conditioners in the $\geq 65,000$ Btu/h to $<240,000$ Btu/h range available on

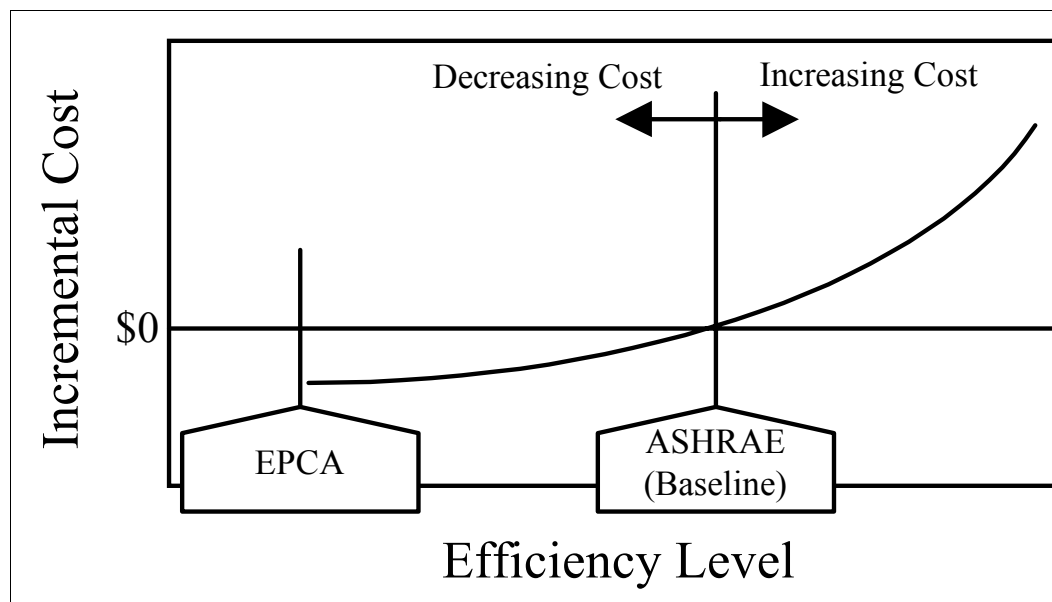


Figure 5.3.1 Range of Efficiency Levels

the market was 11.5 EER. The engineering analysis used reverse engineering on this existing equipment to develop a cost-efficiency curve up to 11.5 EER. Extending the curve beyond 11.5 EER required extrapolation and then verification using design-option analysis modeling. The Department's modeling indicated that, with some additional conventional-type design modifications, such as increases to the size of heat exchangers and modification of the airflow paths (both of which may need new and larger cabinets), the highest practical efficiency level was about 12.0 EER. To limit uncertainty associated with the extrapolated curve beyond 11.5 EER, the maximum efficiency level that DOE evaluated was 12.0 EER. The Department verified the extrapolated cost-efficiency curve using design-option modeling between 11.5 and 12.0 EER. Beyond the 12.0 EER level, the Department will need to consider technologies that are not currently available or non-conventional technologies that are not typically in use by the industry.

Since the time the engineering analysis was conducted, several new commercial unitary air conditioners, with rated efficiency levels up to 12.2 EER, have become available on the market. In addition, the Department recently became aware of one manufacturer that claims an EER level of 13.5 for its commercial unitary air-conditioning equipment. The Department is unaware of any other equipment with a similar EER rating.

5.3.2 Capacities

The four equipment classes that the Department defined cover two capacity ranges: from $\geq 65,000$ Btu/hr to $< 135,000$ Btu/hr and from $\geq 135,000$ Btu/hr to $< 240,000$ Btu/hr. In terms of nominal tons, the capacity ranges are 5.5 to 11 tons and 11.5 to 20 tons, respectively. After reviewing available products in each equipment class and interviewing several of the manufacturers, the Department set the representative capacity (i.e., the equipment capacity to be analyzed in detail for this segment) for the $\geq 65,000$ to $< 135,000$ Btu/hr equipment at 7.5 tons and the baseline capacity of the $\geq 135,000$ to $< 240,000$ Btu/hr equipment at 15 tons. For some manufacturers, these sizes represent their “sweet spots,” i.e., where they have maximized the ratio of cooling capacity to manufacturing cost. Increasing the efficiency of these models would generally be very difficult and expensive because manufacturers have packed as much equipment as they are able into the smallest possible cabinet size. On the other hand, for some manufacturers, the baseline capacities represent the least cost-optimized product. Increasing the efficiency of these products would be less expensive because there is room in the cabinet to increase coil size and add other types of energy-saving devices without moving to a larger cabinet. A majority of the manufacturers that commented about this issue to the Department agree that the 7.5-ton and 15-ton capacities adequately represent the equipment classes and the wide array of design constraints. A few manufacturers, however, suggested that 10-ton and 20-ton units would provide a better representation of the baseline.

5.4 METHODOLOGY OVERVIEW

The methodology for the engineering analysis is a logical, concise, and reproducible process, as illustrated in Figure 5.5.1. At the start of the process, the Department created BOMs for a sample of existing equipment that use R-22 refrigerant by reverse engineering, through either physical teardowns or catalog teardowns (see section 5.5). The Department then estimated the costs of each unit by feeding the BOMs into the cost model (see section 5.6). The next step was to fit curves to the combined cost-efficiency points to represent the cost-efficiency behavior of the industry, and derive confidence intervals that describe the accuracy of the curve (see section 5.7). Using a design-option analysis, DOE then validated the accuracy of the curve between 11.5 EER and 12.0 EER, where there were no existing equipment data points, by using the cost model and performance models to simulate units at higher efficiency levels (see section 5.8). In the last step of the process—the alternative refrigerant analysis—the Department compared the cost-efficiency behavior of R-410a equipment to the R-22 cost-efficiency curve by using the cost model and performance models to simulate R-410a equipment (see section 5.9).

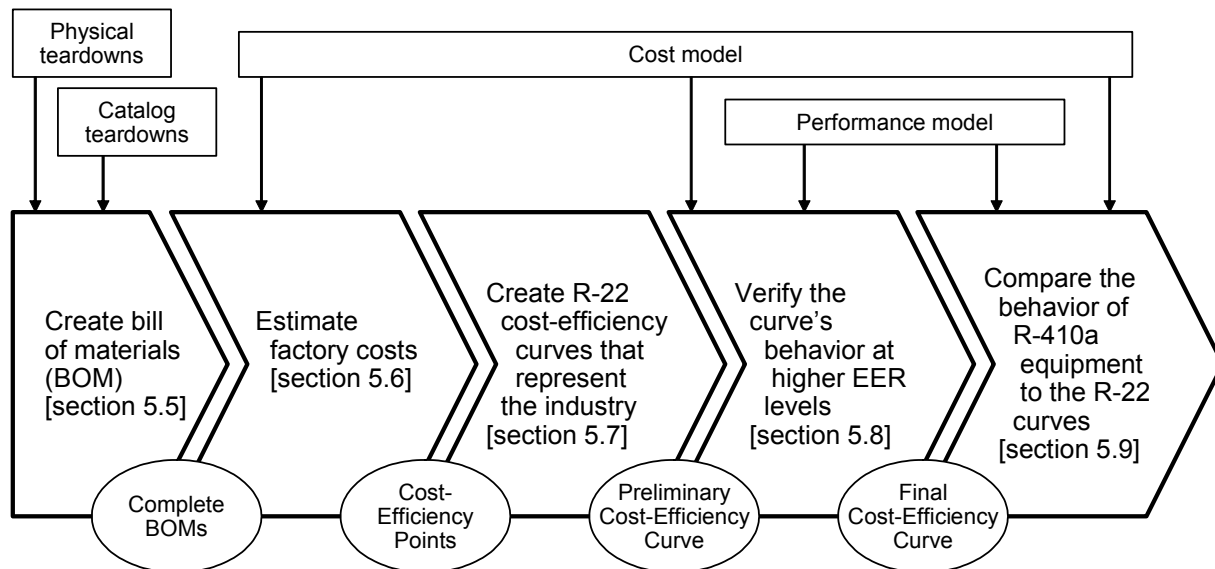


Figure 5.4.1 Illustration of the Engineering Analysis Methodology

5.5 TEARDOWN ANALYSIS

Other than obtaining detailed manufacturing costs directly from a manufacturer, the most accurate method for determining the production cost of a piece of equipment is to disassemble the equipment piece-by-piece and estimate the material and labor cost of each piece, commonly called a physical teardown. A supplementary method, called a catalog teardown, uses published manufacturer catalogs and supplementary component data to estimate the major physical differences between a piece of equipment that has been physically disassembled and another piece of similar equipment. The teardown analysis performed for this engineering analysis includes four physical teardowns and 14 catalog teardowns, for a total of 18 teardowns.

5.5.1 Selection of Units

The Department based its selection of 18 products for teardown, from a pool of 30 products considered in the analysis (see Figure 5.5.1), on clear and consistent guidelines to closely represent the market. The selected equipment exhibit four common characteristics that are key to an accurate and consistent teardown analysis:

1. The selected products, taken together, evenly cover the full range of efficiency levels considered in the analysis (see Tables 5.5.1 and 5.5.2).
2. From any given manufacturer, the Department selected at least one lower-efficiency product and one higher-efficiency product, preferably sharing similar characteristics (e.g., both would be from the same product line).

3. The selected products tend to be from manufacturers that have relatively large market shares in the commercial unitary air-conditioning market, and thus are representative of typical design approaches.
4. The selected products are base products with few, if any, product features or options that add cost without affecting equipment efficiency.

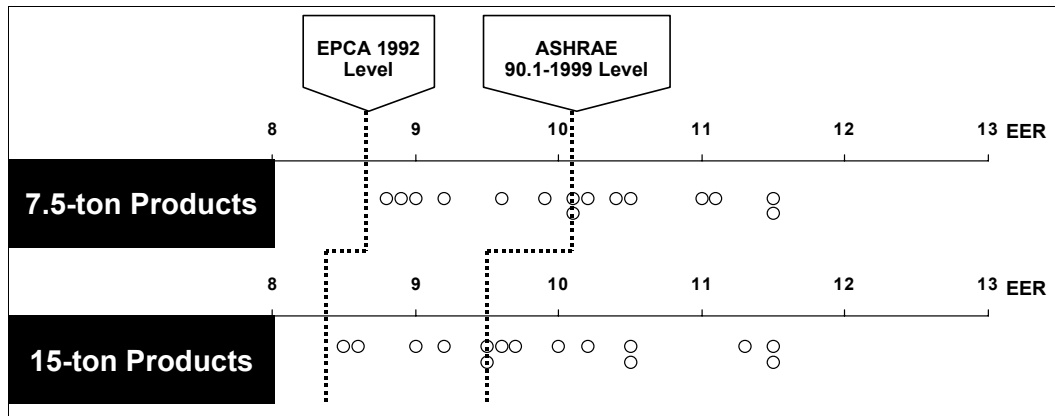


Figure 5.5.1 Efficiency Levels for the 30 Products Considered During the Teardown Analysis

Table 5.5.1 Numbers of Products Considered and Selected from the 7.5-ton Equipment Class

EER range	8.6–9.0	9.1–9.5	9.6–10.0	10.1–10.5	10.6–11.0	11.1–11.5
Products considered	3	1	2	5	1	3
Products selected for physical teardown	0	0	0	1	1	0
Products selected for catalog teardown	2	0	0	2	0	3

Table 5.5.2 Numbers of Products Considered and Selected from the 15-ton Equipment Class

EER range	8.6–9.0	9.1–9.5	9.6–10.0	10.1–10.5	10.6–11.0	11.1–11.5
Products considered	3	3	3	3	0	3
Products selected for physical teardown	0	0	1	0	0	1
Products selected for catalog teardown	1	3	0	1	0	2

The Department does not explicitly identify the efficiency levels of the units it tore down, because doing so could expose sensitive information about individual manufacturers' products.

The physical teardowns were meticulous and provided comprehensive knowledge about the products; the Department characterized each equipment part according to its weight, dimensions, material, quantity, and the manufacturing processes used to fabricate and assemble it. The catalog teardowns were less meticulous because they were limited to public information published by manufacturers, such as coil dimensions, weight, compressor type, and box dimensions. The Department obtained information that was unavailable from the catalog data, such as fan details, number of sensors, or assembly details, from the physical teardowns of a similar product or by estimations based on industry knowledge and discussions with manufacturers.

5.5.2 Generation of Bills of Materials

The end result of each teardown was a structured BOM. Structured BOMs describe each equipment part and its relationship to the other parts, in the estimated order in which manufacturers assembled them. The BOMs describe each fabrication and assembly operation in detail, including the type of equipment needed (e.g., presses, drills) and the process cycle times. The result is a thorough and explicit model of the production process.

The BOMs incorporate all materials, components, and fasteners classified as either raw materials or purchased parts and assemblies. The classification into raw materials or purchased parts is based on the Department's previous industry experience, recent information in trade publications, and discussions with high- and low-volume original equipment manufacturers (OEMs). The Department also visited several manufacturing plants to reinforce its understanding of the industry's current manufacturing practices.

For purchased parts, the purchase price is an estimate based on volume-variable price quotations and detailed discussions with suppliers. For fabricated parts, the price of intermediate materials (e.g., tube, sheet metal) and the cost of transforming them into finished parts is an estimate based on current industry pricing. For a continued discussion of the cost details and assumptions, refer to section 5.6.

5.6 COST MODEL AND DEFINITIONS

Once the Department disassembled selected units and gathered information from manufacturer catalogs on additional products, the next step was to implement an adequate cost model that could translate physical information into costs.

The cost model is based on production activities and divides factory costs into the following categories:

- **Material:** direct and indirect materials;

- **Labor:** fabrication, assembly, and indirect and overhead (burdened) labor; and
- **Overhead:** equipment depreciation, tooling depreciation, building depreciation, utilities, equipment maintenance, and rework.

5.6.1 Cost Definitions

Because there are many different accounting systems and methods in use to monitor costs, and different definitions might generate confusion, the Department defines the above terms as follows:

- **Direct material:** Purchased parts (out-sourced) plus manufactured parts (made in-house).
- **Indirect material:** Material used during manufacturing (e.g., welding rods, adhesive).
- **Fabrication labor:** Labor associated with in-house piece manufacturing.
- **Assembly labor:** Labor associated with final assembly and sub-assemblies.
- **Equipment and plant depreciation:** Money allocated to pay for initial equipment installation and replacement as the production equipment wears out.
- **Tooling depreciation:** Cost for initial tooling (including non-recurring engineering and debugging of the tools) and tooling replacement as it wears out.
- **Building depreciation:** Money allocated to pay for the building space.
- **Utilities:** Electricity, gas, telephones, etc.
- **Equipment maintenance:** Money spent on yearly maintenance, both materials and labor.
- **Indirect labor:** Plant labor that scales directly, based on the number of direct workers (assembly + fabrication). This includes supervisors, technicians, and manufacturing engineering support.
- **Overhead Labor:** Fixed plant labor that is spread over a number of product lines. This includes accounting, quality control, shipping, receiving, floor supervisors, plant managers, office administration, and environmental health and safety. Not included are research and development, corporate management, general administration, and maintenance labor.

- **Rework:** Labor and materials associated with correction of in-plant manufacturing defects.

The Department fed the cost data in all the BOMs—whether they were obtained through physical teardowns, catalog teardowns, or, as discussed in other sections, through numerical simulations—into the cost model. The cost model makes use of specific assumptions to provide cost estimates. The following sections describe these assumptions.

5.6.2 Cost Model Overview

This section provides a general overview of the process the Department used to convert physical information about commercial unitary air conditioners into cost information. The explanation provided here is a simplification, because an exhaustive explanation of the cost modeling techniques is beyond the scope of this document. More information is available in Appendix B.

The first step of the process was to collect physical data on the dimensions, weight, and other information that plays a role in determining the cost of a part. After gathering this information through physical and catalog teardowns, the Department stored the raw information in a spreadsheet organized by major equipment subassemblies. The comprehensive list of all subassemblies and their physical information constitutes the BOM.

To determine the costs, the Department could follow two different paths, depending on whether a subassembly was purchased (out-sourced) or produced in-house. Section 5.6.4, where the major assumptions are described, provides a list of all the purchased subassemblies.

For purchased parts, DOE gathered price quotations from major suppliers at different production volumes. Using this information, the Department was able to build cost-versus-size correlations, such as cost-versus-motor horsepower, cost-versus-condenser fan diameter, and cost-versus-circulating blower wheel diameter. These correlations were very useful during the design option analysis (see section 5.8), when DOE scaled up specific parts and estimated the performance of such “hypothetical” units.

For parts produced in-house, DOE reconstructed manufacturing processes for each part using internal expertise and additional modeling software. For example, for an access panel, the Department estimated the time required for setup, handling, changeover, and punching holes, as well as the number of holes and hits. By repeating this process over and over, the Department was able to assign labor time, equipment utilization, and other important factors to each subassembly in each of the units considered for this analysis. The last step was the conversion of all this information into dollar values. To perform this task, it was necessary to collect information on such factors as labor rates, tooling depreciation, and costs of purchased raw materials. The Department assumed values for these parameters using internal expertise and confidential information available to its contractors. Although most of the assumptions are

manufacturer-specific and cannot be revealed, section 5.6.5 provides a discussion of the ranges used for each specific assumption.

The Department used a slightly different approach to estimate the cost of the condenser and evaporator coils. In this case, the Department used a separate coil model. The coil model converts each coil's physical descriptors into coil costs by calculating the number of fins, hairpin bends, U-bends, take-offs, and coil ends. The model accounts for physical characteristics that affect coil cost. It relies on a process-based cost model that accounts for every fabrication and assembly step. The Department obtained fabrication equipment costs and processing times from equipment vendors, and obtained raw material prices from vendors based on their pricing at the time. More information is available in Appendix B.

In sum, DOE assigned costs of labor, materials, and overhead to each part, including coils, whether purchased or produced in-house. The Department then aggregated single-part costs into major assemblies (e.g., cabinet assembly, condensing unit, evaporator unit, controls, packaging, condenser coil assembly, evaporator coil assembly, furnace, compressors, and shipping) and summarized these costs in a worksheet.

The Department repeated this same process for each unit, representing a specific efficiency level at a given capacity, and mapped the resulting cost-efficiency points to use as building blocks of the cost-efficiency curves.

5.6.3 Cost Model Assumptions

As discussed in the previous section, assumptions about manufacturer practices and cost structure play an important role in estimating the final cost of equipment. During this analysis, some assumptions were different for each specific manufacturer, depending on their strategic position, their manufacturing practices, and their size. The Department aggregated the final cost values to prevent disclosure of confidential information.

In previous rulemakings, the Department used average numbers for all the units considered in order to decrease uncertainty in the first step of the analysis; it later added uncertainty to the average specifications during a separate uncertainty analysis. The Department considers that both the previously-used approach and the current approach are valid to estimate the manufacturing costs. Furthermore, in the current rulemaking, the Department went through the exercise of changing the assumptions to market share-weighted industry averages and compared the results obtained with the two different methods. The Department found no substantial differences, except that the latter approach inherently gives less weight to high-cost producers (which typically have lower market shares), and therefore results in slightly lower costs.

The next sections provide discussions of specific assumptions relating to outsourcing decisions, factory parameters, and production volumes. When the assumptions are manufacturer-specific, they are presented as ranges to prevent disclosure of confidential

information.

5.6.4 Outsourcing

The Department characterized parts based on whether manufacturers purchase them from outside suppliers or fabricate them in-house. For purchased parts, DOE estimated the purchase price. For fabricated parts, DOE estimated the price of intermediate materials (e.g., tube, sheet metal) and the cost of transforming them into finished parts. Whenever possible, the Department obtained price quotes directly from suppliers of the manufacturers of the units being analyzed. For higher-efficiency equipment, DOE assumed the component purchase volume as the baseline; this assumption may have resulted in lower component prices than manufacturers currently pay. Most of the manufacturing operations are carried out in-house, as summarized in Table 5.6.1.

Table 5.6.1 Cost Model Outsourcing Assumptions

Process	Sub-Process	In-House	Outsourced
Tube Forming	Tube Cut	✓	
	Tube Bend	✓	
	Collar	✓	
	Tube Coil	✓	
Sheet Metal	Stamping	✓	
	Press Brake	✓	
	Blanking	✓	
	Turret Punch	✓	
	Plasma Cut	✓	
Welding	Seam Welding	✓	
	Spot Welding	✓	
Machining	Machining Center	✓	
Cutting	Insulation Cut	✓	
Finishing	Paint	✓	
Assembly	Adhesive Bonding	✓	
	Brazing	✓	
	Press Fit	✓	
	Fixture	✓	
	Miscellaneous Assembly Operation	✓	
Final Assembly	Packaging	✓	
	Quality Assurance (Leak Check)	✓	
Charging	Refrigerant Charging	✓	
Molding	Injection Mold		✓
Casting	Sand Cast		✓

Similarly, the Department assumed that the components shown in Table 5.6.2 (on the following page) are purchased from external suppliers.

Table 5.6.2 Purchased Components

Assembly	Purchased Sub-Assemblies
Condensing Unit	Compressor
	Condenser Fan Blade
	Condenser Fan Motor
	Filter/Dryer
Evaporating Unit	Evaporator Fan Motor
	Evaporator Blower
	TXV/Orifice
Controls	Control Boards
	Capacitors, transformers, contactors, etc.
	Line pressure sensors
Heating Section	Gas valve
	Blower motor

5.6.5 Factory Parameters

Factory parameters are manufacturer-specific. For example, low-cost manufacturers are likely to be at the lower end of the ranges presented in the following tables. In the Notice of Proposed Rulemaking (NOPR), a manufacturer impact analysis will examine variability of costs among manufacturers.

The Department based its assumptions for the factory parameters on manufacturer interviews and analysis of common industry practices. Table 5.6.3 lists these assumptions.

Table 5.6.3 Factory Parameter Assumptions

Total Manufacturer Compressor Purchases	400,000–500,000
Annual Production Volume (units/year)	12,000–73,000
Press Lot Size (in days)	0.25–1
Ratio of Designed vs. Actual Production Capacity	1.15–1.3
Direct labor Wages (\$/hr)	\$15.2–18.3
Equipment Uptime	85–95%
Assembly Factor (ratio of actual to ideal)	1.25–2
Tooling Depreciation (in years)	4–5
Fringe Benefit Ratio	35–65%
Pre-painted Steel Cost (\$/lb)	\$0.30–0.41
Building Cost (\$/sq.ft.)	80–120
Refrigerant 22 Cost (\$/lb)	0.85–1.2
Worker Downtime	10–20%
Building Life (in years)	25–40
Property Taxes (as % of building cost)	0.6–2.1%
Rework Rate	0–8%

5.7 INDUSTRY COST-EFFICIENCY CURVES

Creating the industry cost-efficiency curves was a three-step process that consisted of plotting the raw data points as cost versus efficiency, translating the cost data from absolute costs to incremental costs, and fitting a least-squares curve and 95 percent confidence interval to the incremental cost-versus-efficiency data.

According to discussions with manufacturers and observations of the cost-efficiency data, DOE learned that cost behaves exponentially as EER increases. In other words, as air conditioners become more efficient, it becomes increasingly difficult and costly to increase efficiency to the next higher level. This is partly because traditional lower-cost design changes, such as increasing coil area or upgrading compressor efficiency, may not suffice. For example, the design may already use the highest-efficiency compressor, and increasing the coil area any more may degrade its performance by changing its refrigerant temperatures to be above or below acceptable limits. Therefore, DOE derived the cost-efficiency curves using an exponential curve-fit.

5.7.1 Plotting Absolute Cost Versus Efficiency

The cost model analysis created cost estimates for each of the 18 teardown products, as detailed in section 5.6. The cost output from the model includes all manufacturing costs and a manufacturer's markup, which covers corporate overhead expenses. This combined cost, called "absolute cost" for purposes of discussion, is the price at which the manufacturer sells the product to distributors, resellers, and similar parties—it is not the final cost to the end-user, because it does not include the distribution markups.

The absolute cost from the model is plotted as a function of each product's efficiency in terms of its EER. Manufacturers publish EER values for each of their products, according to ARI specifications. Each of the resulting two plots of absolute cost versus efficiency—one for the 7.5-ton equipment class and one for the 15-ton equipment class—has nine data points.

The Department does not present any absolute costs in this document, because doing so could expose sensitive information about individual manufacturers' products.

5.7.2 Translating Absolute Cost to Incremental Cost

For the next step in the process of creating the industry cost-efficiency curves, the Department translated the absolute costs into incremental costs. Incremental cost, as discussed in Section 5.3, is the cost of raising equipment efficiency from the baseline efficiency level (ASHRAE 90.1 efficiency level) to some incrementally higher efficiency level.

As illustrated in Figure 5.7.1, the cost translation process shifts the absolute costs of each manufacturer's products so that the incremental cost of their products equals zero at the baseline ASHRAE 90.1 efficiency level described in section 5.3.1. The Department shifts costs for products made by the same manufacturer equally, but shifts costs for products made by different manufacturers independently. To do this, DOE first fits an exponential curve to each manufacturer's product data points separately. Then, DOE shifts each curve down until it intersects the y axis (incremental cost equal to zero) at the baseline efficiency. The Department shifts all data points for a given manufacturer down by the same amount as the curve, so that the resulting data points represent incremental cost versus EER. The Department then discards the individual manufacturer curve-fits, and the analysis continues with the translated cost data points.

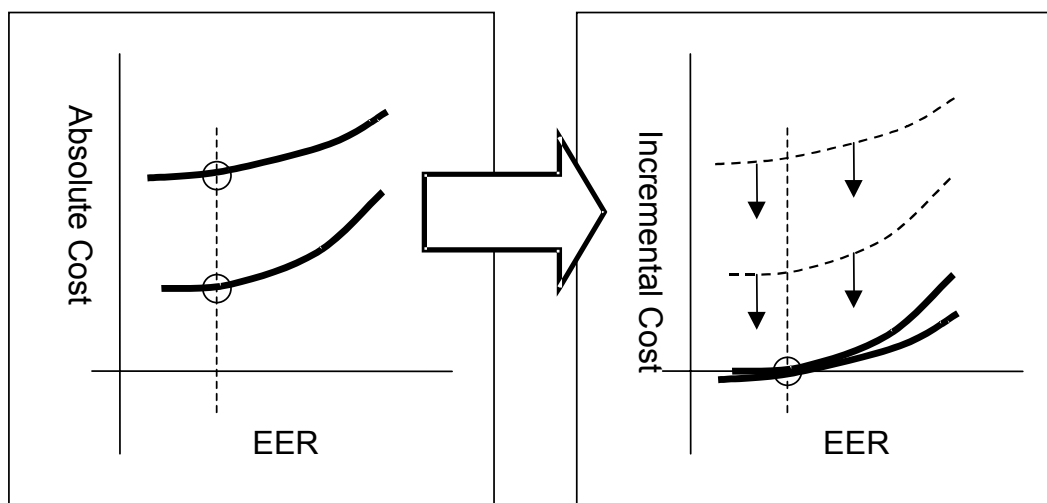


Figure 5.7.1 Illustration of the Cost Translation Process

5.7.3 Fitting the Cost-Efficiency Curve and Confidence Interval

For the final step in the process of creating the industry cost-efficiency curves, DOE fit an exponential curve to the translated cost-EER data points, using a least-squares regression analysis. The result is an industry cost-efficiency curve for each of the two equipment classes (7.5-ton and 15-ton), which represents the costs for the industry to incrementally increase equipment efficiency above the ASHRAE 90.1 baseline levels. The curves do not represent any single manufacturer, nor do they describe any variance between manufacturers; they represent the industry as a whole. The regression analysis also produced confidence intervals for the cost-efficiency curves.

The Department used the regression analysis tool included in the Microsoft Excel 97 software program to perform the least-squares regression analysis for creating the exponential curve-fits and confidence intervals. A least-squares regression analysis establishes a curve of a given type (exponential in this case) that “best fits” the data. A confidence interval describes the accuracy of the curve, based on the scatter of the data. In this case, DOE used a 95 percent confidence interval, which means that if the costs of a sample of products are at the same efficiency level, 95 times out of 100 their “best fit” cost will be within the confidence interval.^a

Figures 5.7.2 and 5.7.3 present the industry cost-efficiency curves and confidence intervals, while Tables 5.7.1 and 5.7.2 show the results in tabular form. Because DOE did not consider data points with efficiency levels above 11.5 EER, DOE extrapolated the portion of the curves between 11.5 EER and 12.0 EER. The accuracy of this portion of the curves was uncertain at this point in the analysis. The design option analysis described in section 5.8 further discusses the level of accuracy in this portion of the curves.

^a Mendenhall and Sincich, Statistics for Engineering and the Sciences, 4th Edition, 1995.

Table 5.7.1 The 7.5-ton Equipment Class Cost-Efficiency Relationship and Confidence Interval

	10.1-EER	10.5-EER	11.0-EER	11.5-EER	12.0-EER
Incremental Cost	\$0	\$47 +/- \$14	\$139 +/- \$41	\$292 +/- \$85	\$543 +/- \$159

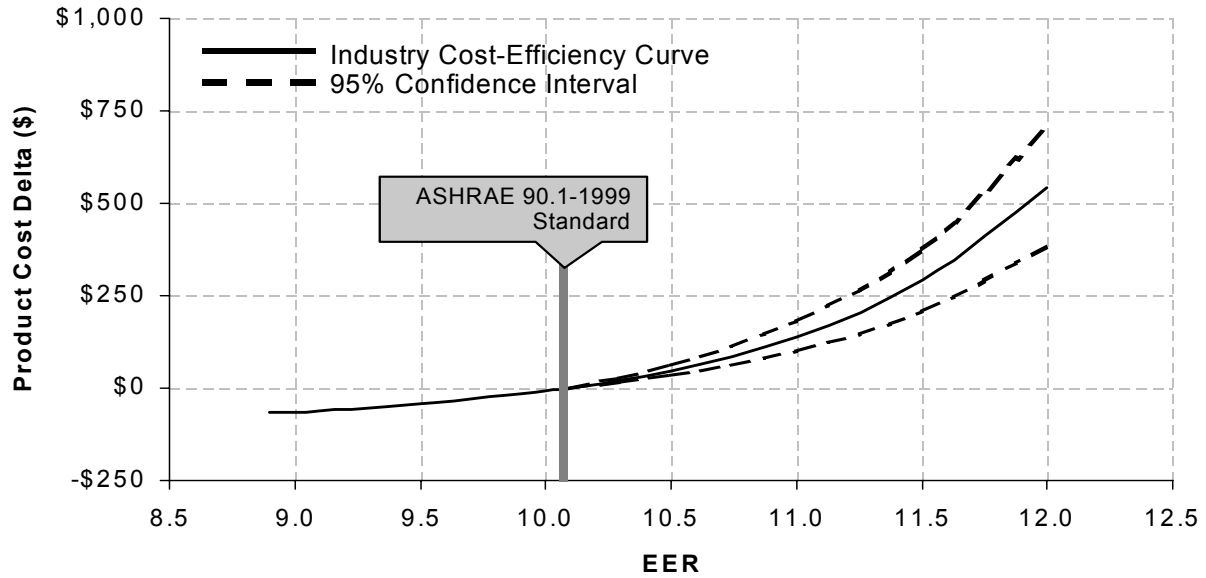


Figure 5.7.2 The 7.5-ton Equipment Class Cost-Efficiency Curve and Confidence Interval

Table 5.7.2 The 15-ton Equipment Class Cost-Efficiency Relationship and Confidence Interval

	9.5-EER	10.0-EER	10.5-EER	11.0-EER	11.5-EER	12.0-EER
Incremental Cost	\$0	\$62 +/- \$35	\$165 +/- \$94	\$334 +/- \$191	\$613 +/- \$351	\$1072 +/- \$615

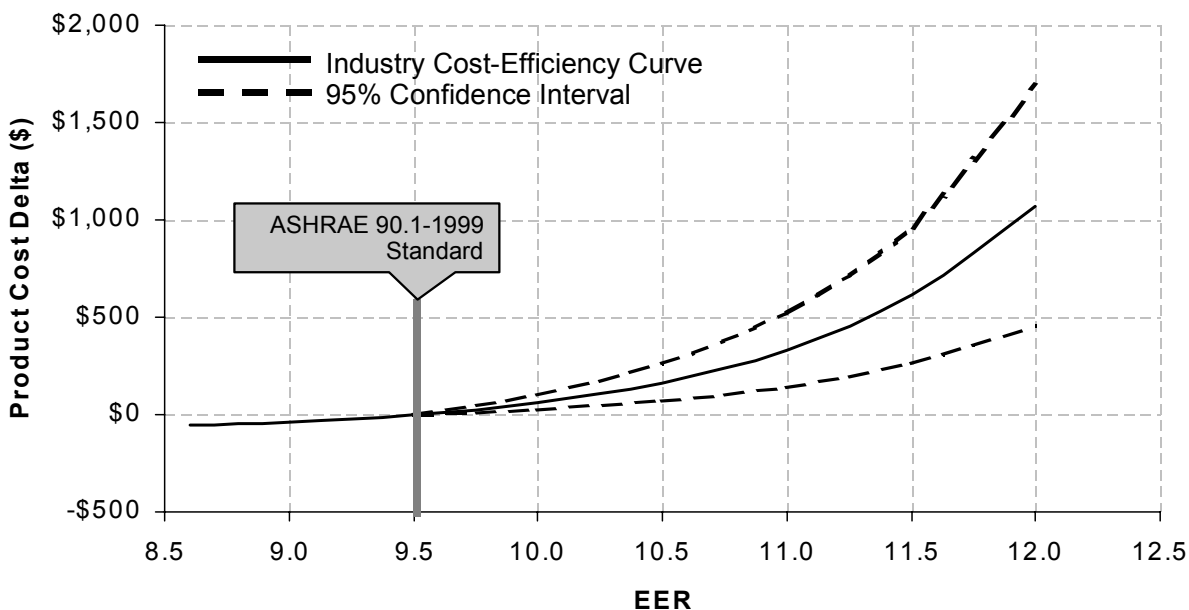


Figure 5.7.3 The 15-ton Equipment Class Cost-Efficiency Curve and Confidence Interval

The industry cost-efficiency curve for the 15-ton equipment class is steeper than the one for the 7.5-ton equipment class, in part because the larger equipment is bigger and has more material. For example, a manufacturer may increase efficiency in both 7.5-ton and 15-ton equipment by increasing condenser coil area. To get the same EER increase, the condenser area must be increased more for the 15-ton equipment than for the 7.5-ton equipment. This leads to higher direct material costs as well as higher labor costs and other indirect costs for the 15-ton equipment.

The confidence interval is wider for the 15-ton equipment than for the 7.5-ton equipment, in part because there was more scatter in the incremental cost data among the manufacturers for the larger-capacity equipment.

5.8 DESIGN OPTION ANALYSIS

The purpose of the design option analysis is to validate the accuracy of the cost-efficiency curves at efficiency levels between 11.5 EER and 12.0 EER. As mentioned in section 5.3.1 and illustrated in Figure 5.5.2, there were no products in that efficiency range evaluated during the teardown analysis, so there were no data points available for the curve-fit. Consequently, the accuracy of the curve in this range is not known. However, the design option analysis simulates equipment with efficiency levels above 11.5 EER and compares its costs with the costs predicted by extending the existing curve.

The simulated design option data points do not influence the industry cost-efficiency curves. The Department did not consider these data points in the curve-fitting procedures discussed in section 5.7.3; they served primarily as a check on the accuracy of the existing curves between 11.5 EER and 12.0 EER.

To simulate equipment, the Department used a combination of modeling tools and techniques, as detailed in Appendix C. The Department performed the refrigerant-side heat transfer and balance calculations using the Oak Ridge National Laboratory's (ORNL) heat pump model, using compressor performance data for commercially available compressors. The Department used a custom heat exchanger software program to perform the air-side heat transfer and pressure drop calculations. The Department used a combination of manufacturer data, test data, published fan performance curves, and published motor performance curves to determine fan power and airflow.

The first step in the analysis simulated the performance of the four existing products that DOE physically tore down, as described in section 5.5. Additionally, DOE had one of the products tested (according to Air-Conditioning and Refrigeration Institute (ARI) testing standards) at a third-party testing laboratory to measure its specific performance parameters, including refrigerant pressures and temperatures, mass flows, capacity, and EER. The Department used the test data to construct and calibrate the model (see Table 5.8.1), and then performed various design option combinations to simulate equipment with increased efficiencies. Through discussions with manufacturers and using engineering judgement, the Department established several design guidelines to limit the design option simulations (see Table C.3.1 in Appendix C).

The Department estimated the costs of the simulated equipment using the cost model discussed in section 5.6.

Table 5.8.1 Comparison Table for the Model Calibration Versus Test Data

	Predicted by Model	Measured by ITS Testing	Difference
Capacity (Btu/hr)	91,037	92,741**	-1.8%
EER	10.334	10.45**	-1.1%
Compressor Power (W)	7,325	7,430 +/- 2.0%	-1.4%
Evaporator Blower Power (W)	910	880 +/- 2.0%	+3.4%
Condenser Fan Power (W)	575	562 +/- 2.0%	+2.3%
Evaporator Pressure (PSIA)	96.8	98.7 +/- 2.0%	-1.9%
Evaporator Temperature (°F)	48.8	Average: 50** (48.7 - 51.2)†	1.2 °F
Condenser Pressure (PSIA)	279.2	282.2 +/- 2.0%	-1.1%
Condenser Temperature (°F)	121.3	Average: 122.1** (120.6 - 123.7) †	0.8 °F

* Using ARI Test "A" methods

** Calculated from measured data

† Range calculated from pressure error band

5.8.1 Accuracy of Industry Cost-Efficiency Curves above 11.5 EER

Based on the design option analysis, the general trend of the curve between 11.5 EER and 12.0 EER is generally accurate, because none of the design option points lies outside of the 95 percent prediction interval.

Similar to the confidence interval described in section 5.7.3, a prediction interval describes the accuracy of the curve-fit in predicting the cost of any single unit. In this case, the Department used a 95 percent prediction interval, which means that, for any single unit at a certain efficiency level, 95 times out of 100 its cost will be within the prediction interval.^b Figure 5.8.1 shows the simulated design option points and prediction interval for the 7.5-ton equipment class, and Figure 5.8.2 shows the simulated design option points and prediction interval for the 15-ton equipment class.

^b Mendenhall and Sincich, Statistics for Engineering and the Sciences, 4th Edition, 1995.

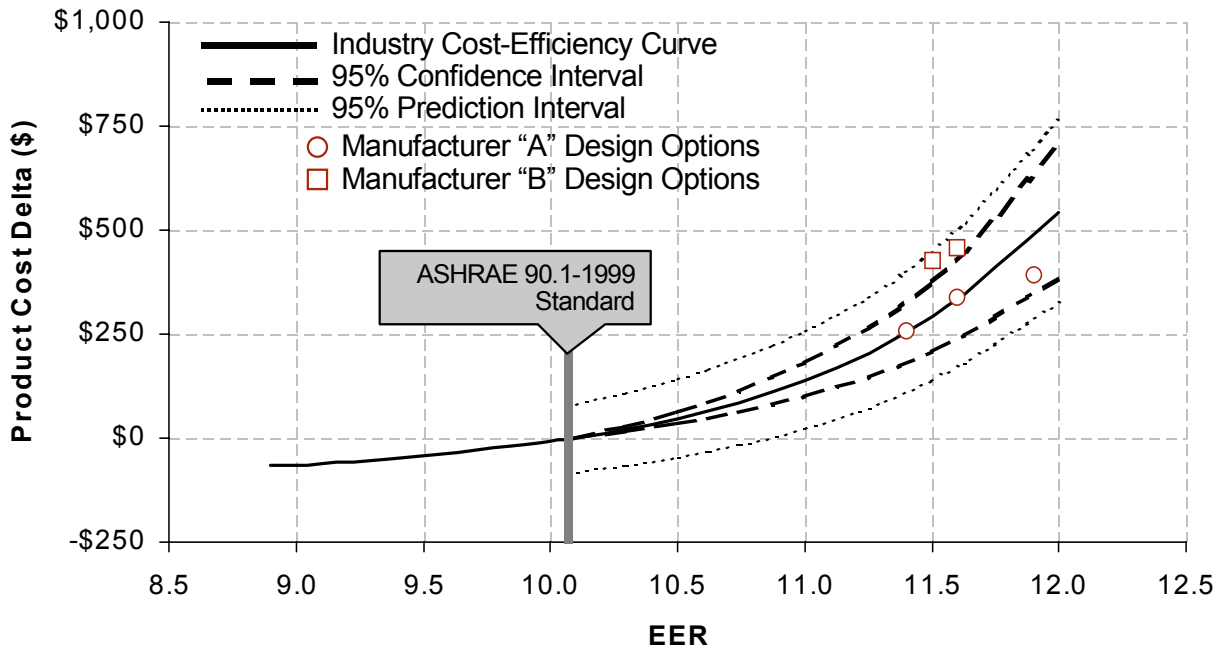


Figure 5.8.1 7.5-ton Cost-Efficiency Curve with Simulated Design Option Points

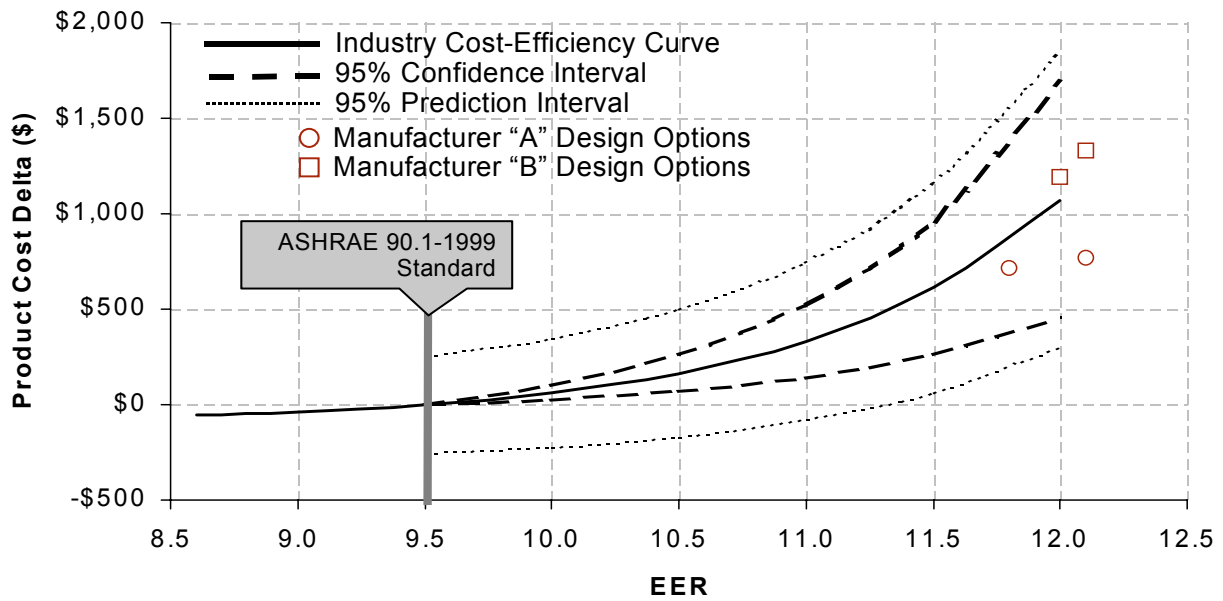


Figure 5.8.2 15-ton Cost-Efficiency Curve with Simulated Design Option Points

5.9 ALTERNATIVE REFRIGERANT ANALYSIS

The purpose of the alternative refrigerant analysis is to identify any substantive differences between the cost-efficiency behavior of R-410a and R-22 equipment. For this analysis, the Department simulated R-410a equipment using the same performance models described in section 5.8, calculated their costs using the same cost model described in section 5.6, and compared those simulated data points to the existing R-22 cost-efficiency curve. The Department only considered simulations because, at the time the analysis was conducted, there were no commercially available R-410a products in the 7.5-ton or 15-ton equipment classes.

The Department constructed baseline R-410a equipment models, starting with existing R-22 models (see section 5.8), swapping out compressor maps, and using design options to bring the R-410a equipment to the same efficiency level as the R-22 equipment. The Department then performed various design option combinations to simulate equipment with increased efficiencies.

5.9.1 Alternative Refrigerant Selection

Two refrigerants, R-410a and R-407c, are currently under consideration as substitutes for R-22, which will be phased out of new equipment in 2010. While R-407c has similar pressure-temperature characteristics as R-22 and thus is more easily adapted to existing R-22 designs, it is less efficient. By contrast, R-410a operates at higher pressures than R-22, thus requiring substantial redesign of R-22 equipment. However, R-410a offers efficiency benefits relative to R-407c. Consequently, the consensus of manufacturers contacted by the Department during the rulemaking process was that R-410a is the most likely replacement for R-22 in new commercial unitary equipment as the phaseout of R-22 approaches.

5.9.2 Alternative Refrigerant Product Availability

Although some unitary air-conditioning products using R-410a are commercially available, none was available when the engineering analysis was conducted in the capacity range that the analysis covers. However, since the analysis was conducted, the Department has learned that there is one R-410a commercial unitary air conditioner now available on the market in the 15-ton representative capacity. The majority of the R-410a products are currently being sold primarily for residential applications. Consequently, the Department's analysis compared the design differences between R-22 and R-410a products in smaller packaged units (i.e., 5-ton units) to gain general engineering insight.

As components, there are R-410a compressors that are commercially available in sizes that can be used in commercial unitary air conditioners rated $\geq 65,000$ through $< 240,000$ Btu/h. The Department used performance characteristics from those compressors for input to its engineering analysis.

5.9.3 Differences Between R-22 and R-410a

Because R-410a equipment was not available in the equipment classes considered during the engineering analysis, the Department made six assumptions about simulated R-410a equipment. The Department based each assumption on detailed discussions with manufacturers and engineering calculations.

The Department assumed that:

1. Although the design pressures of R-410a are higher than R-22, the diameter and thickness of tubing will be the same. This is based on interviews with manufacturers and comparisons of five-ton R-22 products to five-ton R-410a products.
2. R-410a compressors will cost approximately four percent more in the long term (i.e., high production volume) than R-22 compressors with similar capacities, according to communications with an executive at a leading compressor manufacturer.
3. R-410a scroll compressors are less efficient than comparable R-22 scroll compressors, but more efficient than low-efficiency R-22 reciprocating compressors, based on product literature from leading compressor manufacturers.
4. Higher heat transfer coefficients of R-410a allow slightly lower condensing temperatures than are possible with R-22. The minimum condensing temperature is reduced by one degree Fahrenheit according to log-mean temperature difference (LMTD) heat exchanger calculations that use a 15 percent higher heat transfer coefficient.
5. Evaporating temperature limits for R-410a systems are the same as for R-22 systems.
6. Long-term cost of R-410a refrigerant in bulk quantities will be approximately \$3/lb, according to personal communications with a leading refrigerant manufacturer.

5.9.4 Cost-Efficiency Curve for R-410a Equipment

In view of the alternative refrigerant analysis, there is no evidence that the general cost-efficiency behavior of R-410a equipment in the 7.5-ton and 15-ton equipment classes over the range of efficiencies in this analysis is substantially different from the R-22 cost-efficiency behavior. Figures 5.9.1 and 5.9.2 show the R-410a design option points overlaid on the R-22 cost-efficiency curves. In general, the cost-efficiency trends of R-22 and R-410a are similar.

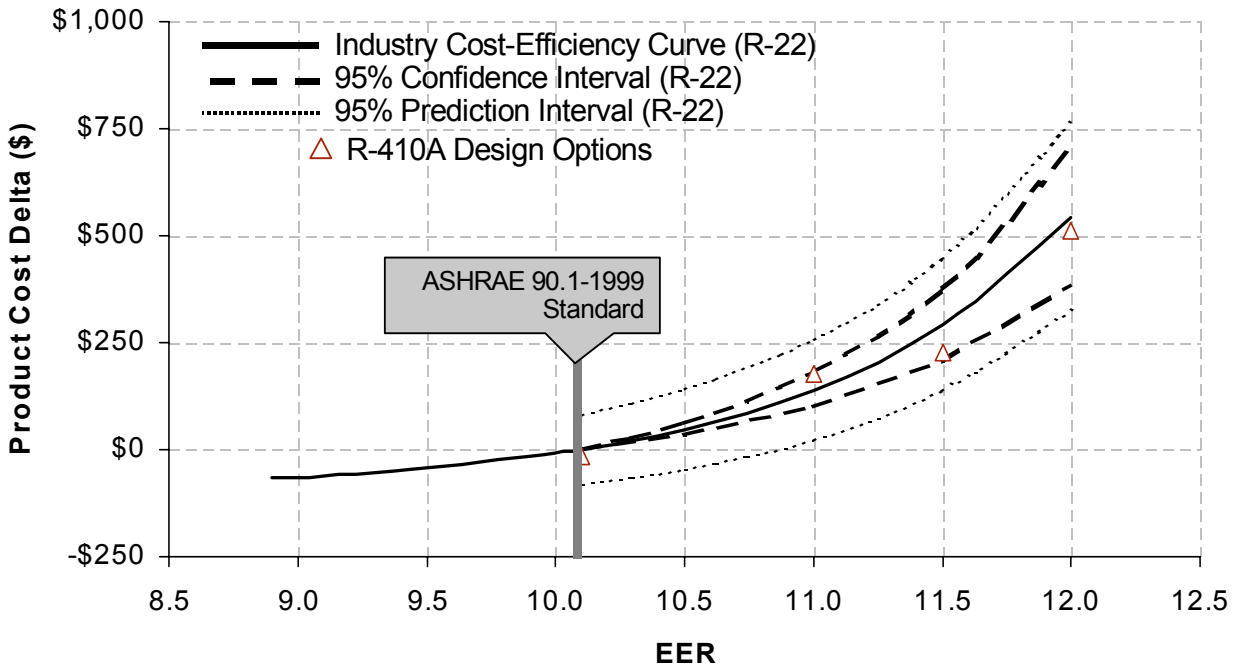


Figure 5.9.1 7.5-ton R-22 Cost-Efficiency Curve with R-410a Design Option Points Overlaid

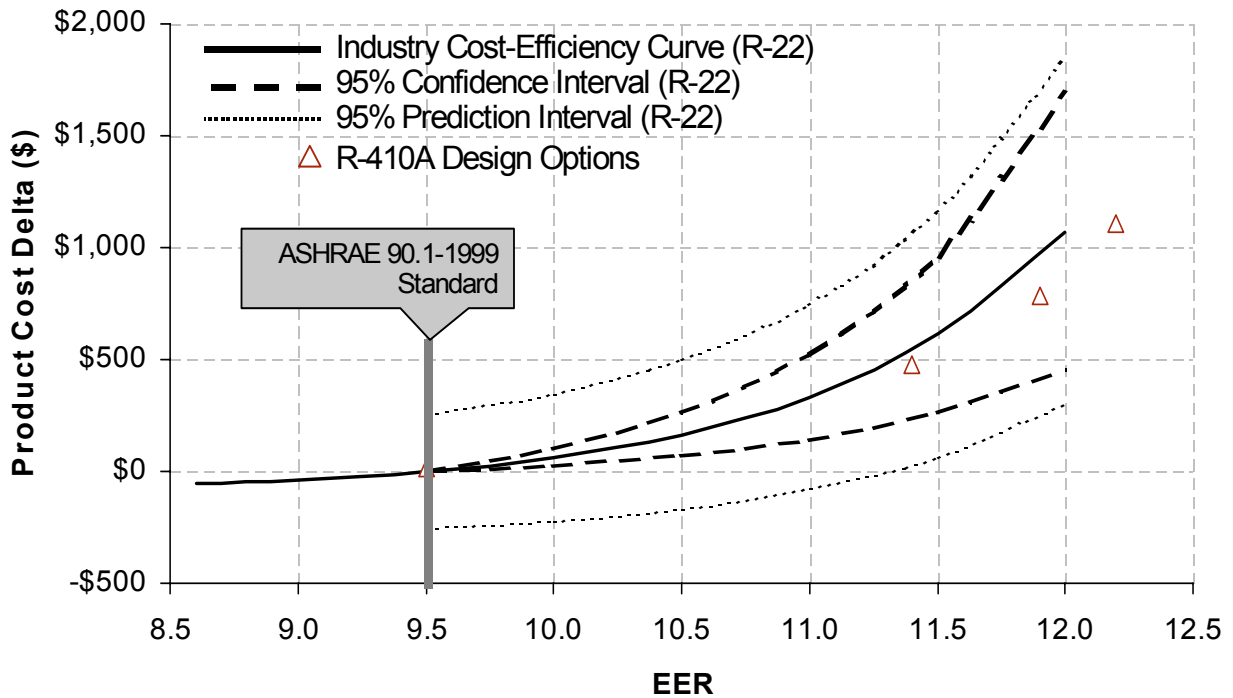


Figure 5.9.2 15-ton R-22 Cost-Efficiency Curve with R-410a Design Option Points Overlaid